THE PREDICTABILITY OF WEATHER AND CLIMATE
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CHAPTER X

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PREDICTABILITY OF TROPICAL INTRASEASONAL VARIABILITY

Duane E. Waliser
Jet Propulsion Laboratory, MS 183-505
California Institute of Technology
4800 Oak Grove Drive, Pasadena, CA 91109
818-393-4094 (tel); 818 354 0966 (fax)

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1. Introduction

Not long after the development of numerical weather forecasting in the 1950s, predictability studies emerged with the desire to determine the theoretical limits associated with deterministic weather forecasting (e.g., Thompson, 1957; Lorenz, 1965; 1982; Lorenz, 2005; Palmer, 2005). Estimating these limits helped to better quantify the capabilities and skill-level of operational weather forecast models and determine how far and fast the community should press the embryonic field of numerical weather forecasting. Numerical predictability studies expanded to include the ocean and the climate scale with the advent of seasonal-to-interannual forecasting based on the El Nino Southern Oscillation (ENSO) (e.g., Cane et al., 1986; Graham and Barnett, 1995; Kirtman et al., 1997; Barnston et al., 1999; Anderson, 2005; Hagedorn et al., 2005; Shukla and Kinter, 2005). In this case, it was of interest to understand the theoretical limits for predicting tropical Pacific Ocean sea surface temperature (SST) anomalies, and then in turn their implications for predicting monthly or seasonal anomalies of mid-latitude circulation, temperature and rainfall.

Very recently, predictability at the intraseasonal time scale (i.e. lead times of about 2 weeks to 2 months) has garnered great interest (Schubert et al., 2002; Waliser et al., 2003a; ECMWF, 2004). This evolution of research and operations in regards to specific prediction regimes (i.e. weather, seasonal and then intraseasonal) has mimicked quite remarkably that anticipated by John von Neumann (1955, relevant excerpt can be found in Waliser 2005). His foresight followed from traditional mathematical approaches and was thus based on the expectation that the simplifying extremes of the prediction problem would be tackled first. In this case, the short lead-time, "initial-value problem" of weather forecasting, followed by the "boundary-value problem" associated with seasonal-to-interannual forecasting, and then finally the regime in between (i.e. intraseasonal) where neither extreme holds. Given the long-standing maturity of weather forecasting and the more recent establishment of operational seasonal-to-interannual forecasting, there is now a fairly well defined gap in prediction capability at the intraseasonal time scale. While the simple existence of this gap has certainly contributed to the community's growing interest in this time scale, attention has also been stimulated by the recognition that a number of noteworthy phenomena and processes have the potential to lend predictability at this intervening time scale. These phenomena and processes include the Arctic Oscillation (AO)/North Atlantic Oscillation (NAO), the Pacific North American (PNA) pattern, the Madden-Julian Oscillation (MJO), soil moisture and SST variability, and the intermittent occurrence of mid-latitude blocking. Improved predictions of these phenomena and processes have the potential to provide significant practical benefits which include useful low-frequency weather forecasts over much of the tropics – an area where forecasting has typically been exceptionally challenging (Waliser et al., 1999b; Wheeler and Weickmann, 2001; Newman et al., 2003; Waliser et al., 2003b; Barlow et al., 2005; Hoskins, 2005; Wheeler and McBride, 2005), skillful forecasts of active and break monsoon conditions (Waliser et al., 2003c; Liess et al., 2004; Webster and Hoyos, 2004; Webster et al., 2005), and improved extra-tropical surface temperature and precipitation predictions (Higgins et al., 2000; Kirtman et al., 2001; Thompson and Wallace, 2001; Whitaker and Weickmann, 2001; Baldwin et al., 2003; Bond and Vecchi, 2003; Koster et al., 2004; Vecchi and Bond, 2004).

While the discussion and associated studies cited above indicate that a number of intraseasonal phenomena and processes have bearing on the intraseasonal (a.k.a. subseasonal) prediction problem, the MJO in particular has been singled out as one of the most underexploited in terms of lending potential for near-term gains in forecast skill (Schubert et al., 2002; Waliser et al., 2003a; ECMWF, 2004; Waliser et al., 2005). This focus on the MJO is not only due to the characteristics of the phenomena itself and the direct impact it has on a broad region of the Tropics at the intraseasonal time scale but also because of the influences the MJO has on time scales of variability outside this band. For the case of weather, the MJO – through its relatively slow modulations of tropical diabatic heating - offers the hope for extending (at least occasionally) the range of useful forecasts of weather and/or weather statistics (e.g., Ferranti et al., 1990; Jones et al., 2004a), including tropical storms and hurricanes (Maloney and Hartmann, 2000a; b; Mo, 2000; Goswami et al., 2003) and extreme US west coast rainfall events (Mo, 1999; Higgins et al., 2000; Jones, 2000). For the seasonal-to-interannual time scale, the MJO represents an intermittent yet important component of atmospheric forcing (e.g., westerly wind bursts and the development of El Nino) as well as a key component atmospheric "noise" that can limit the skill associated with forecasts at this time scale (e.g., McPhaden, 1999; Moore and Kleeman, 1999; Kessler and Kleeman, 2000; Zhang et al., 2001).

Given the importance of the MJO to considerations of weather and climate predictability as outlined above, this chapter reviews predictability issues associated with tropical intraseasonal variability, with a particular emphasis on the MJO. In the following section, a brief observational description of the MJO is presented, including its seasonal and interannual modulations. In section 3, the physical theory underlying this variability, particularly as it relates to the phenomenon's predictability, is briefly reviewed. In Section 4, an assessment of our present-day understanding of the predictability of the MJO is given. In Section 5, a number of practical considerations of MJO prediction are discussed. Section 6 concludes with a discussion of the outstanding issues and questions regarding future research and progress in this area. Additional reviews of the above and related material can be found in (Lau and Waliser, 2005; Waliser, 2005a; b; Zhang, 2005)

2. Physical Description

The dominant form of intraseasonal atmospheric variability, particularly in terms of rainfall generation and global reach of influence, is most often referred to as the Madden-Julian Oscillation [MJO; also known as the 30-60 day, 40-50 day, and intraseasonal oscillation (ISO)] after its discoverers (Madden and Julian, 1971; 1994; 2005). The left panels of Figure 1 illustrate the canonical space-time structure of rainfall and low-level winds in the tropics associated with an MJO "event" during boreal winter, with the interval between maps being 12.5 days. These maps illustrate its eastward propagation and equatorially-trapped character. The left panels of Figure 2 show similar information but for mid-tropospheric geopotential heights and upper-level winds. Comparison of the corresponding upper and lower tropical wind fields emphasize the baroclinic nature of its wind anomalies, with upper tropospheric divergence (convergence) occurring in conjunction with positive (negative) rainfall anomalies and vice versa for the lower troposphere. In addition, it can be seen that the MJO has a global scale. At upper levels, wind anomalies, are primarily characterized by wavenumber 1. At lower levels, wind and rain anomalies are primarily characterized by wavenumber 2, with a significant modulation by the relatively warmer (cooler) eastern (western) hemisphere background state. For example, over the Indian and west Pacific Oceans, there is evidence of considerable interaction between the wind and rainfall anomalies. In these regions, where the coupling between the convection and warm surface waters is strong, the oscillation propagates rather slowly, about 5-10 m/s. However, once the disturbances reach the vicinity of the Date Line, and thus cooler eastern Pacific Ocean equatorial waters, the convection tends to subside and propagate southeastward into the SPCZ. Beyond the dateline, the disturbance is primarily evident only in the near-equatorial wind field with characteristics similar to a dry Kelvin wave with a speed of about 15-20 m/s or greater (Hendon and Salby, 1994).

Another important feature associated with the MJO, especially in relation to its connections to mid-latitudes, is its off-equatorial structure and variability. From the left panels of Figure 1 and Figure 2 there is evidence of off-equatorial Rossby wave gyres that straddle the near-equatorial rainfall anomalies. For example, in the composite maps at lag +12.5 days, the positive rainfall (i.e. heating) anomaly is located over the Maritime continent. Associated with this are upper-level cyclonic (anticyclonic) gyres to the northeast and southeast (northwest and southwest) centered at latitudes of about 20^{o}. These gyres are more easily identified in the life-cycle analysis of the MJO by Hendon and Salby (1994) and are consistent with the circulation that is expected in association with a near-equatorial tropospheric heating anomaly (Matsuno, 1966; Gill, 1980). One of the important manifestations of these tropical heating and subtropical streamfunction anomalies is that they act as Rossby wave sources for mid-latitude variability (e.g., Weickmann, 1983; Liebmann and Hartmann, 1984; Weickmann et al., 1985; Lau and Phillips, 1986; Sardeshmukh and Hoskins, 1988; Berbery and Noguespaegle, 1993). For example, the +12.5-day lag map of Figure 2 shows evidence of a wave train emanating from the tropics and extending poleward and eastward over the Pacific Ocean and North America. Such connections with the extra-tropics have important ramifications for mid-latitude weather variability, regime changes and forecasting capabilities (e.g., Ferranti et al., 1990; Higgins et al., 2000; Jones et al., 2004a).

The ISV characteristics discussed above tend to be most strongly exhibited during the boreal winter and spring when the Indo-Pacific warm pool is centered at or near the equator. In the boreal summer, the MJO is still present although its spatial variability and propagation characteristics are modified by the changes associated with the annual cycle. The right panels of Figure 1 and Figure 2 illustrate the canonical space-time structure of the MJO in boreal summer (for more in depth observational descriptions see recent reviews by Goswami, 2005; Hsu, 2005). Note that the summertime manifestation of the MJO is often referred to as the Intraseasonal Oscillation (ISO), the boreal summer ISO, or monsoon ISO (MISO). Examination of the rainfall map at lag 0 days shows that positive rainfall anomalies in the western and central Indian Ocean for the boreal summer case occur in conjunction with negative rainfall anomalies over a region extending between India and the western equatorial Pacific. This system then appears to propagate both eastward – similar to the boreal winter case - and northward (Yasunari, 1979; Lau and Chan, 1986; Lawrence and Webster, 2002; Hsu, 2005). As with the boreal winter case, the associated mid-latitude variability occurs primarily in the winter hemisphere.

Most relevant to the present discussion of predictability is the large spatial scale and slow evolution of the rainfall patterns in Figure 1 relative to typical synoptic-scale weather features. These characteristics suggest a measure of predictability at a time scale on the order of weeks (e.g., Waliser et al., 1999b). This feature, along with their somewhat regular occurrence, their impact on the Asian-Australian monsoons, as well as their influence on extra-tropical weather patterns motivate the need to develop the capability to predict these "events" and improve our understanding of their predictability. To gain an appreciation for their dramatic impact on the Asian and Australian monsoons, Figure 3 shows the annual cycle of rainfall and the anomalous evolution of unfiltered and filtered rainfall over India and northern Australia for a sample of three years. These time series emphasize the overall dominance, apart from the annual variation, of the intraseasonal time scale on these monsoon systems, including its obvious role in dictating active and break phases. In addition, the three years sampled is enough to illustrate that the MJO exhibits a considerable amount of year-to-year variability (e.g., Ferranti et al., 1997; Hendon et al., 1999; Slingo et al., 1999; Lawrence and Webster, 2001; Teng and Wang, 2003).

While the diagrams in Figure 1 and Figure 2 illustrates what might be considered typical winter and summer MJO events, it is important to recognize that these events have considerably more complexity in reality. For example, the study by Wang and Rui (1990), and later by Jones et al. (2003), have further diagnosed the "synoptic climatology" of tropical MJO events, including their seasonal modulation. These studies show for example that boreal winter events display considerable variation in the longitude that the convection develops and/or dissipates. Moreover, it is well known that the convection associated with MJO events typically propagates further east during El Nino events (e.g., Kessler, 2001). For the boreal summer case, Kemball-Cook and Wang (2001) show that there is a systematic intra-seasonal change in the spatial structure and propagation characteristics of the MJO. In the early part of the summer (e.g., May-June), the off-equatorial variability is generally found west of Southeast Asia and the Maritime Continent, while in the later part of the summer, it expands to include much of the northwestern Tropical Pacific.

In addition to the above complexities, there are also finer scale structures embedded in the MJO that deserve mention. For example, studies by Nakazawa (1988), Lau et al. (1991), and Chen et al. (1996) have shown that the convective variability organizes on a wide range of time and space scales within the large-scale anomalies that are emphasized in Figure 1. In addition, the latitudinal asymmetry of the boreal summer MJO makes its evolution and physical description more complicated than the boreal winter case, where the latter is generally thought of as an eastward propagating, convectively-coupled, equatorially-trapped wave complex. These aspects of the physical description also hold for the boreal summer case, particularly in the Indian Ocean and far western Pacific. However, the summertime hemisphere in the boreal summer case experiences a relatively larger increase in SST and surface moisture, and an accompanying enhancement in the large-scale easterly vertical shear, than for the boreal winter case. These features, along with the land-sea distribution in the area, promote the emanation and growth of Rossby waves that are forced by the near-equatorial convection anomalies (Li and Wang, 1994; Wang and Xie, 1996; 1997; Kemball-Cook and Wang, 2001; Lawrence and Webster, 2002). The overall eastward propagation of the large-scale, near-equatorial convective anomaly, combined with the inherent westward-propagation of these Rossby waves (Matsuno, 1966) and a number of mechanisms that promote their northward propagation of the latter (e.g., Jiang et al., 2004), largely account for the appearance of the eastward-propagating, northwest-southeast tilted, large-scale "rainband" evident in Figure 1. Other noteworthy features associated with the boreal summer MJO include what is known as the climatological ISO (CISO, e.g., Wang and Xu, 1997) and significant variability at the 10-20 day time scale. Elaboration on the above detailed features of the MJO as well as more comprehensive aspects of MJO theory are beyond the scope of this chapter and the reader is referred to a number of recent reviews on these subjects (Chang, 2004; Goswami, 2005; Hsu, 2005; Waliser, 2005a; Wang, 2005; Wheeler and McBride, 2005).

3. Predictability

By the late 1980's, many characteristics of the MJO were fairly well documented and it was clear that it was a somewhat well defined phenomenon with a number of reproducible features from one event to another as well as in events from one year to the next. Given this, and the degree that research had shown a number of important interactions of the MJO with other features of our weather and climate system, it was an obvious step to consider MJO forecasting in more earnest. Since numerical weather and climate models typically had, and still have, a relatively poor representation of the MJO (e.g., Slingo et al., 1996; Waliser et al., 2003e; Allen et al., 2005; Slingo et al., 2005), a natural avenue to consider was the development of empirical models. Along with the possibility of providing more skillful forecasts than numerical methods available at the time, this avenue also provided a means to establish an initial estimate of the predictability limit for the MJO – at least that which could be ascertained from the observations alone.

There were a number of different approaches and data sets used in these empirical studies. For example, von Storch and Xu (1990) examined Principal Oscillating Patterns of equatorial 200 mb velocity potential anomalies with an emphasis on boreal winter. The model of Waliser et al. (1999b) was based on a field-to-field Singular Value Decomposition that used previous and present pentads of outgoing longwave radiation (OLR) to predict future pentads of OLR with separate models developed for boreal winter and summer conditions. Lo and Hendon (2000) developed a lag regression model that used as predictors the first two and first three principal components of spatially filtered OLR and 200 hPa streamfunction, respectively, to predict the evolution of the OLR and 200 hPa streamfunction anomalies associated with the boreal winter MJO. A similar strategy was used by Jones et al. (2004b). Mo (2001) utilized empirical basis functions in time by using a combination of singular spectrum analysis for the filtering and identification of the principal modes of variability and the maximum entropy method for the forecasting component. The procedure was applied to monitor and forecast OLR anomalies in the intraseasonal band over both the Indian–Pacific sector as well as the pan-American region. In a quite different approach, Wheeler and Weickmann (2001) utilized tropical wave theory (Matsuno, 1966; Wheeler and Kiladis, 1999) as the basis for their filtering and forecasting technique. In order to monitor and predict the evolution of a given mode of interest, near-equatorial time-longitude sections were Fourier analyzed in two dimensions and then the specific zonal wavenumbers and frequencies associated with the mode(s) of interest (e.g., MJO) were retained, and then the modified spectrum was inverse Fourier analyzed. Goswami and Xavier (2003) identified all active and break phases associated with boreal summer MJO events and then as a means for prediction calculated the typical (i.e. ensemble average) transition from active to break (and break to active) conditions as a function of lead-time. Most recently, Webster and Hoyas (2004) have developed a physically-based, multi-predictor, Bayesian model to predict regional rainfall and river discharge associated with the Asian monsoon, with a particular emphasis on intraseasonal variations over India. A number of additional empirical schemes that have relevance to real-time prediction will be discussed in Section 4.

The above discussion gives a flavor of the types of empirical MJO models that have been developed to date. For the most part, each of the above studies developed their model on a given portion of the observed record and then tested it on an independent portion. Glossing over the details, the upshot of these studies is that empirical models demonstrate useful predictive skill for the MJO on the order of 15-25 days or more, depending on the spatial scale and quantity being predicted. However, as with any empirical model, these models are limited in the totality of the weather and climate system they can predict, their ability to adapt to arbitrary conditions, and their ability to take advantage of known physical constraints. Thus one might conclude that if dynamical models had a realistic representation of the MJO, this limit might be extended somewhat. While the majority of dynamical models to date still exhibit significant shortcomings in terms of their MJO simulation – particularly if pressed to do operational prediction, there have been a few models, or versions of models, that have demonstrated success at representing a number of the principal features of the MJO (Slingo et al., 1996; Sperber et al., 1997; Waliser et al., 1999a; Kemball-Cook et al., 2002; Maloney, 2002; Fu et al., 2003; Zheng et al., 2004). This degree of model success at least provides the means to perform "perfect-model", or so-called "twin-predictability", experiments to ascertain an estimate of the theoretical limits of prediction for the MJO. In this case, "forecasts" are verified against others that only differ in the initial conditions (e.g., Lorenz, 1965;

Shukla, 1985; Palmer, 2005). This approach was taken in two recent studies by Waliser et al. (2003b; 2003c). In this case, the experiments were performed with the NASA Goddard Laboratory for Atmospheres (GLA) general circulation model (GCM) (Kalnay et al., 1983; Sud and Walker, 1992). In a number of studies, this model has been shown to exhibit a relatively realistic MJO (Slingo et al., 1996; Sperber et al., 1997; Waliser et al., 2003d) with reasonable amplitude, propagation speed, surface flux characteristics, seasonal modulation, and interannual variability (Waliser et al., 2001). One of its principal deficiencies is its relatively weak variability in the equatorial Indian Ocean, a problem quite common in atmospheric GCMs (AGCMs, Waliser et al., 2003d).

For these studies, a 10-year control simulation using specified annual cycle SSTs was performed in order to provide initial conditions from which to perform an ensemble of twin predictability experiments. Note that this analysis was performed separately on boreal winter and summer MJO activity (e.g., left and right panels of Figure 1, respectively). The following discussion describes the boreal winter study (Waliser et al., 2003b) but the methods are quite similar for the boreal summer analog (Waliser et al., 2003c) of which a few results are also mentioned. Initial conditions were taken from periods of strong MJO activity identified via extended empirical orthogonal function (EOF) analysis of 30-90 day bandpassed tropical rainfall during the October through April season. From the above analysis, 15 cases were chosen when the MJO convection was located over the Indian Ocean, Maritime continent, western Pacific Ocean, and central Pacific Ocean, respectively, making 60 cases in total. In addition, 15 cases were selected which exhibited very little to no MJO activity. Two different sets of small random perturbations, determined in a rather ad hoc and simplistic manner, were added to these 75 initial states. Simulations were then performed for 90 days from each of these 150 perturbed initial conditions (cf., Buizza, 2005; Kalnay et al., 2005).

A measure of potential predictability was constructed based on a ratio of the signal associated with the MJO, in terms of bandpassed (30-90 day filter) rainfall or 200 hPa velocity potential (VP200), and the mean square difference between sets of twin (bandpassed) forecasts. Predictability was considered useful if this ratio was greater than one, and thus if the mean square error was less than the signal associated with the MJO. The results, shown in Figure 4, indicate that useful predictability for this model's MJO extends out to about 20 to 30 days for VP200 and to about 10 to 15 days for rainfall. This is in contrast to the time scales of useful predictability for the model's weather, or for cases in which the MJO is absent. In these latter cases, the predictability limit is roughly 12 days for VP200 and 7 days for rainfall. Note that these latter two regimes are related, in that when the MJO is quiescent, the model lacks a low-frequency component that might help it retain predictability over long time scales and is in a regime where the processes and time scales of weather are the only phenomena left to provide predictability. Additional support for this conclusion was demonstrated from a predictability analysis on EOF decompositions of the model data (Waliser et al., 2003b). This analysis shows more definitively that the enhanced predictability derives from the (~two) EOF modes that represent the MJO variability in the model. In addition to the above, the predictability measure exhibits modest dependence on the phase of the MJO, with greater predictability for the convective phase at short (< ~5 days) lead times and for the suppressed phase at longer (> ~15 days) lead times. This result appears consistent with the empirical model results of Goswami and Xavier (2003) that showed break monsoon phases to be more predictable than active phases.

Additional experiments have been carried out to assess the sensitivity of the results above to changes in background state. For example, the study by Waliser et al. (2003c) was performed in an analogous fashion, although with more cases (N=168), to examine the predictability limits associated with the boreal summer MJO. The left panels of Figure 5 show maps that depict the size of the MJO "signal" in terms of VP200 at lead times of 5, 15 and 25 days. Due to the relatively long time scale of the MJO, this signal remains roughly constant over this period. The right panels show the associated mean squared error at the same lead times. Evident is the fact that the error is generally less than the signal even up to 25 days indicating predictability at these lead times. As expected, the maps show that the predictable VP200 signal is limited to the tropical regions where the MJO has an impact on this quantity. A similar diagram for rainfall (not shown here), indicates useful predictability out to about 15 days, with the geographic extent being even more limited. The plots in Figure 6 provide a more quantitative illustration of the above for a select region within the area of high MJO variability. The lead time at which the error and signal intersect can roughly be equated to the limit of predictability (i.e. where the predictability ratio discussed above becomes one). Similar to the boreal winter results, the limit of predictability for the upper level circulation (i.e. VP200) and rainfall for the boreal summer MJO is about 25-30 days and 15-20 days, respectively. Consistent with the discussion above, this figure also demonstrates that when the MJO cases analyzed are divided into strong versus weak cases, predictability associated with the strong cases is enhanced.

Predictability measures were also examined under El Nino and La Nina conditions. In this case, analogous experiments to those described above for the boreal winter case were performed but with imposed El Nino and La Nina SST anomalies. To construct these anomalies, the observed SST anomalies between September and the following August for the El Nino years of 1957, 1972, 1982, 1986, 1991 and 1997 were averaged together. This 12-month "raw" anomaly was then subject to a Fourier analysis, retaining only the lowest three harmonics. This step ensured that the imposed anomaly consisted of only low-frequency and, more importantly, periodic variations. To account for signal loss in the compositing and filtering procedure, the resulting anomaly was multiplied by a factor of 2, and then added to the climatological SSTs to provide a perpetual 12-month evolving El Nino condition. The procedure was performed exactly the same for the La Nina case, except using June through the following May anomalies for the La Nina years 1950, 1954, 1956, 1956, 1970, 1973, 1974, 1988. The 12-month means of the anomalous El Nino and La Nina SST patterns are shown in the upper panels of Figure 7. For each case, 10-year simulations were performed and then analyzed in the same manner as described above.

The middle and lower panels of Figure 7 illustrate that the predictability of the model's MJO is considerably enhanced (diminished) for the imposed El Nino (La Nina) conditions. Examination of the results shows that part of these changes derives from the changes in the SST in the central Pacific and the associated extension (contraction) of the MJO propagation path for the El Nino (La Nina) case. More substantial is the fact that overall the MJO signal, meaning the amplitude of the typical event analyzed, is considerably larger (smaller) for the El Nino (La Nina) case than for the control (i.e. climatological SST) case. Given a somewhat similar error growth rate, this change in signal also promotes the changes observed to the model's MJO predictability. This latter aspect raises an interesting question relative to the studies performed to date that examine the relation between interannual SST variability and MJO activity (e.g., Gualdi et al., 1999; Hendon et al., 1999; Slingo et al., 1999), which for the most part (even for this same model, Waliser et al., 2001) have found little or no relation, particularly for the boreal winter case. The results here suggest that perpetually warm or cool anomalous SST conditions might have a considerable impact on the MJO (e.g., Slingo et al., 1999; Zveryaev, 2002) while the observed intermittent interannual SST variability does not.

While the results from these numerical studies are encouraging from the view point of intraseasonal prediction, and are not entirely inconsistent with the sorts of complimentary empirical studies mentioned above, there are a number of issues to consider that might impact the limit of predictability estimate they provide. First, the GLA model employed has been shown to have too much high frequency, low wave-number activity (Slingo et al. 1996). Relative to the MJO, this variability would be considered to be un-organized, errant convective activity that may erode the relatively smooth evolution of the MJO and thus diminish its predictability. Second, these simulations were carried out with fixed climatological SST values. A previous study with this model showed that coupled SSTs tend to have an enhancing and organizing influence on the MJO, making it stronger and more coherent (Waliser et al., 1999a). Thus the exclusion of SST coupling may lead to an underestimate of the predictability as well (cf., Timmermann and Jin, 2005).

There are also a number of aspects associated with the model and/or analysis to suggest that the above results might over estimate the predictability of the MJO. The first is that the model's coarse resolution and inherent reduced degrees of freedom relative to the true atmosphere may limit the amount of small-scale variability that would typically erode large time and space scale variability. However, it is important to note in this regard that the low order EOFs of intraseasonally filtered model output typically do not capture as much variability as analogous EOFs of observed quantities. Thus the model's MJO itself still has room to be more robust and coherent which would tend to enhance predictability. In addition to model shortcomings, the simple manner that perturbations were added to the initial conditions may also lead to an overestimate of the predictability. The perturbation structure and the size of the perturbations may be too conservative and not adequately represent the type of initial condition error that would be found in an operational context. However, even if that is the case, it would seem that adequate size "initial" errors would occur in the forecast in a matter of a day or two and thus one would expect this aspect to overestimate the predictability by only a couple days, if at all.

In order to address some of the uncertainties mentioned above, an analogous study for boreal summer conditions using the ECHAM AGCM has recently been undertaken (Liess et al., 2004). The modeling and analysis framework is similar to that described above with two important exceptions. First, rather than select a large number of events (i.e. ~15-20) for each of four phases of the boreal summer MJO (i.e. convection in Indian Ocean, Maritime continent, Southeast Asia, northwest tropical Pacific) and performing only a few (i.e. 2) perturbation experiments with each, this study has selected the 3 strongest events in a 10-year simulation and then performed a larger ensemble of forecasts for each of the four phases (i.e. 15). In addition, rather than use rather simply determined perturbations, this study uses the breeding method (Toth and Kalnay, 1993; Cai et al., 2003). Figure 8 shows the combined results from all twelve 15-member ensemble MJO forecasts using the ECHAM5 AGCM. The data for the figure are taken from 90 ºE to 120 ºE and 10 ºN to 20ºN for 30-90 day bandpass filtered rainfall (upper) and VP200 (lower) anomalies. These results suggest that the boreal summer MJO has dynamical predictability with lead times potentially up to and beyond 30 days. These lead times are at least as large, if not larger, than those found in Waliser et al. studies highlighted above. However, it should be noted that the event analyzed here is a particularly robust and strong one for the model, and those above were based on both strong and moderate size events which could account for the difference. In any case, even though the above results do not take into account systematic model bias relative to the observations, they, along with many of the other studies discussed above, indicate that a promising avenue and time scale of operational prediction lies ahead.

4. Practical Considerations

Based on the motivating factors presented in the Introduction and the promising results derived from the empirical forecast and dynamical predictability studies discussed in the previous section, there is ample reason to push towards an operational MJO predictive capability. Ideally, it would be most convenient if our present-day numerical weather forecast models could demonstrate skill at MJO simulation and prediction. If this was the case, our medium-to-long range forecasts could simply be extended to provide useful subseasonal predictions of the MJO and the ancillary weather and circulation systems it interacts with (e.g., tropical storms, mid-latitude flows). Unfortunately, due to the poor representation of the MJO by most GCMs, this avenue cannot be readily or fully exploited (Allen et al., 2005; Palmer, 2005). This has been found to be particularly true in the few studies carried out to test the predictive skill of the MJO in operational weather forecast models. For example, the studies by Chen and Alpert (1990), Lau and Chang (1992), Jones et al. (2000), Hendon et al. (2000) were all performed on the most recent or previous versions of the National Oceanic and Atmospheric Administration's (NOAA's) National Centers for Environmental Prediction (NCEP) (or NMC) medium range forecast (MRF) model's Dynamic Extended Range Forecasts (DERFs). In general these studies only found useful skill out to about 7-10 days for MJO-related variability, and were simply hampered by MJO variability that was too weak and/or that propagated too fast. Probably the most optimistic set of forecast skill experiments for the MJO were a set of Asian monsoon MJO case studies performed by Krishnamurti et al. (1990; 1992; 1995). The novel approach in these cases was that an attempt was made to filter out the "weather" time and space scales from the initial conditions and leave only the "low-frequency modes". In this case, the results demonstrated useful forecast skill out to 3-4 weeks, however there are some uncertainties associated with making such a technique operational as well with the manner the boundary-layer forcing (i.e. SST) was handled. For a more thorough discussion of above studies, as well as the real-time efforts highlighted below, see Waliser (2005b).

Given the need for forecast capability at the intraseasonal time scale, along with the poor representation of the MJO in dynamical models, a number of real-time efforts have been developed based on empirical methods. These include those based on a number of the schemes mentioned above, such as Wheeler and Weickmann (2001), Jones et al. (2004b), Lo and Hendon (2000) as improved on by Wheeler and Hendon (2003), and Webster and Hoyas (2004). In addition, van den Dool and Saha (2002) have recently applied the empirical wave propagating (EWP) technique developed by Van den Dool and Qin (1996) to forecast the MJO. EWP is a 'phase-shifting' technique that allows one, in the diagnostic step, to determine the amplitude-weighted-average climatological phase speed of anomaly waves (e.g., equatorial MJO), where the waves are represented as either zonal or spherical harmonics. The diagnostic step results in a table of phase speeds for waves in the anomaly field as a function of zonal wavenumber, calendar month and latitude, based on the observed data. This technique has shown to be particularly well suited for empirically forecasting the large-scale upper-level anomalies (e.g., VP200) associated with the MJO.

In quite a different approach, stemming from a somewhat different and/or more comprehensive objectives, Newman et al. (2003) have developed and implemented a real-time forecasting scheme that has applicability to the MJO based on what is often referred to as the Linear Inverse Model (LIM, Winkler et al., 2001). The LIM is based on NCEP/NCAR reanalysis data (Kalnay et al., 1996) that has had the annual cycle removed, been smoothed with a 7-day running mean filter, gridded to T21 spatial resolution, and been reduced by EOF decomposition. The specific fields used include global 250 and 750 hPa streamfunction and tropical column-integrated diabatic heating. For the boreal winter (summer) model, the first 30 (30) streamfunction and 7 (20) diabatic heating EOFs are used. In this model, historical data are used to define the relationship between a given state (i.e. a weekly average) and conditions one week later, with the process being iterated to produce multi-week forecasts. The advantage of the model is that it includes both tropical and extratropical quantities in the forecasts. In this way, the interaction between the two can be more readily examined and diagnosed. The results in Figure 9 show that for tropical forecasts of diabatic heating, the LIM slightly outperforms a research version of the (dynamic) NCEP MRF model at lead times of 2 weeks, for both northern hemisphere summer and winter, particularly in regions where the MJO is most strongly associated with the diabatic heating field.

Based on the sorts of activities and preliminary successes described above, along with the needs to take a more systematic approach to diagnosing problems in dynamical forecasts of the MJO, an experimental MJO prediction program has recently been implemented (Waliser et al., 2005). The formal components of this program arose from two parallel streams of activity. The first was the occurrence of the intraseasonal workshop mentioned in the Introduction (Schubert et al., 2002) and the recognition of the importance of the MJO in regards to the potential skill to be had from intraseasonal predictions. The second stream of activity ensued from the priorities and recommendations of the US CLIVAR Asian-Australian Monsoon Working Group. These streams of activity led to the identification of forecast contributors (which include many of the efforts described above), the formulation of an initial framework for such a program, the identification of a sponsor that could provide scientific and technical support as well as serve as the data host/server (i.e. NOAA's Climate Diagnostics Center), and a more formal implementation meeting (Waliser et al., 2003a).

The motivation for the above experimental program involves not only the obvious objective of forecasting MJO variability but also to serve as a basis for model intercomparison studies. The latter includes using the forecasts and biases in model error growth as a means to learn more about, and possibly rectify, model shortcomings but also includes using the empirical models to provide some measure of the expectations that should be attributed to the dynamical models in terms of MJO predictive skill. In addition, it is hoped that this program and its forecasts will provide a modeling resource to those trying diagnose interactions between the MJO and other aspects of weather and intraseasonal variability (e.g., PNA, AO). While the immediate goal of the program has been to assemble and provide what is readily available from the community in terms of 2-4 week forecasts of the MJO, there are a number of challenges faced by such an effort that are worth highlighting. The most notable involve how to deal with forecast models that have yet or routinely do not have a lead-dependent forecast climatology which is necessary to remove a model's systematic biases, the manner the MJO signal(s) are to be extracted from the heterogeneous set of models (e.g., empirical and numerical), the degree that coupled models and ensembles need to be or can be incorporated into the project, and of course the general logistical problems of dealing with assembling a very non-uniform set of forecast products from different agencies and researchers in near real-time and streamlining them for the purpose of this project.

In terms of ocean coupling, a number of recent studies (Wu et al., 2002; Fu and Wang, 2004; Zheng et al., 2004) have indicated that accurate MJO predictions can only be produced if SST coupling is accounted for in dynamical forecasts. For example, the plots in Figure 10, taken from Zheng et al. (2004), show that the observed (i.e. quadrature) phase relationship between MJO-related convection and SST anomalies is properly represented in their coupled GCM (CGCM). However, the relationship becomes incorrectly represented (i.e. nearly in phase) in the corresponding AGCM simulations that use specified SSTs taken from the CGCM simulations.

These results hold for boreal summer and winter, the Indian Ocean and western Pacific Ocean, as well as another GCM configuration (Fu and Wang, 2004). One of the most important implications of this result is that if specified SSTs are used in a prediction environment, phase errors in tropical convection on the order of 5-10 days (or 5-20º longitude) will occur. This is substantial when considering the local tropical prediction but also problematic when considering the impact on the extra-tropics. Thus, subseasonal (e.g., MJO) predictions must include ocean coupling - i.e. a "two-tier" prediction framework is inadequate.

5. Discussion

The review of the studies examined in this chapter was meant to summarize what is known regarding the predictability of tropical intraseasonal variability as well as the current state of affairs of our ability to predict it. Notable is the fact that nearly all the studies presented were primarily based on the MJO, which although is not the only mode of intraseasonal variability in the Tropics, it is the most dominant. This limitation suggests that further research is needed to examine the predictability of other intraseasonal variations in the Tropics. This includes SST variability both related to and unrelated to the MJO (e.g., Kirtman et al., 2001) as well as intrinsic SST modes (e.g. tropical instability waves, see Kessler, 2005), higher-frequency subseasonal modes associated with the Asian monsoon (e.g. Annamalai et al., 1999; Gadgil, 2003) as well as variability over Africa (Matthews, 2004) and Pan America (Mo and Paegle, 2005).

Based on the material presented, there appears enough evidence to suggest that MJO predictions can be approached with considerable optimism as our present capabilities seem far from saturating their potential, and once exploited operationally, they will provide a unique and important bridge between the more established areas of weather and seasonal-to-interannual prediction. One of our greatest challenges remains to develop robust and realistic representations of the MJO in our weather and climate forecast models (Slingo et al., 2005). Once we have such a capability, we not only have a means to improve predictions of low-frequency weather variations in the tropics that are directly impacted by the MJO, including the onsets and breaks of the Asian and Australian summer monsoons, but we will also likely improve forecasts associated with a number of processes remote to the MJO (see Introduction).

To develop reliable prediction capabilities of intraseasonal variability and improve our understanding of its limits of predictability, there are a number of areas that warrant investigation. This includes a more complete understanding of the role that coupling to the ocean plays in maintaining, and in particular forecasting, the MJO. In addition, there has been virtually no research done on model initialization / data assimilation issues in terms of what are the critical criteria to meet in order to adequately initialize the state of the MJO (Kalnay et al., 2005; Simmons, 2005; Thorpe and Petersen, 2005). Related to this are issues regarding the importance of the basic state of the forecast model and how an incorrect basic state might negatively impact the maintenance and propagation of the MJO (e.g., Hendon, 2000; Inness et al., 2003; Sperber et al., 2003; Liess and Bengtsson, 2004; Allen et al., 2005). Additional avenues of research include exploring the methods proposed by Krishnamurti et al. (1990) with other present-day forecast systems and on more MJO cases as well as exploring the possibility of assimilating empirically-derived forecasts of the MJO into extended-range weather forecasts in order to improve their forecasts of the MJO as well as the remote processes and secondary circulations they interact with. Research is also needed to evaluate the best use of ensemble predictions at the intraseasonal time scale (Buizza, 2005; Kalnay et al., 2005), including super-ensemble techniques (Krishnamurti et al., 2005). It is also possible that the interactions with soil moisture and vegetation might be an influential factor that needs to be accounted for in the types of subseasonal predictions discussed here (Koster et al., 2004). In addition to the above, there is clearly a need for additional dynamical predictability studies of the MJO using other GCMs as well as more sensitivity studies to test the effects of SST coupling and ENSO state, the impacts from/on mid-latitude variability, and the influence of the size and type of initial condition perturbations and definition of predictability. Finally, there has been very little consideration of the economic benefits of intraseasonal predictions, namely where and when such predictions would have the greatest economic benefit, at what specific lead times, and for what sectors and industries (Richardson, 2005).

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FIGURES

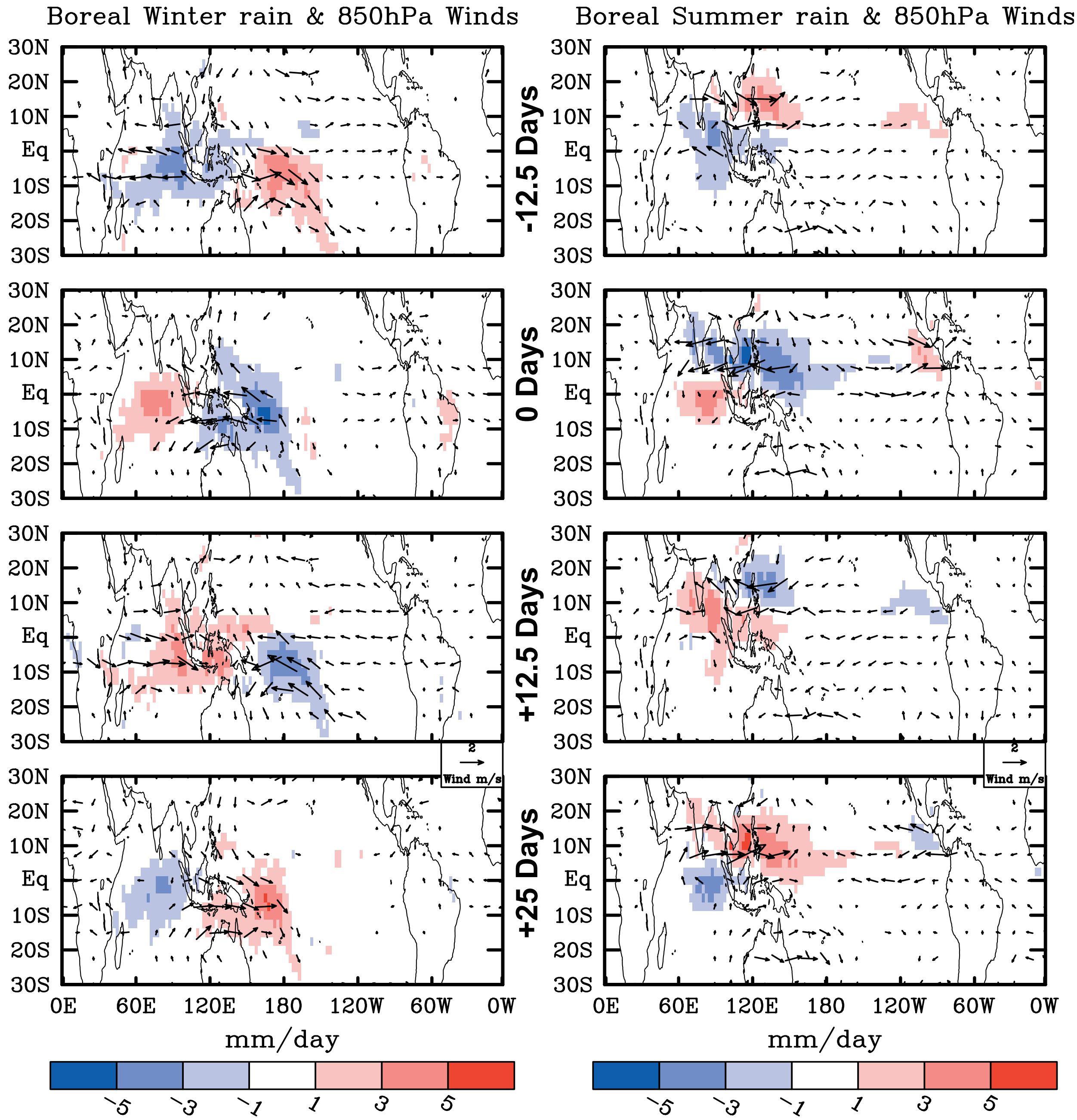

Figure 1. Canonical structure of an MJO event based on 5-day average (i.e. pentad) NCEP/NCAR Reanalysis (Kalnay et al., 1996) and CMAP rainfall data (Xie and Arkin, 1997) from 1979-2000. Data were bandpassed filtered with a 30-90 day filter and then separated into boreal winter (Nov-Apr) and summer (May-Oct). Extended EOF (EEOF) analysis with +/-5 pentad lags was performed on tropical rainfall (30N-30S, 30E to 180E) to identify the dominant "mode" for the winter and summer separately. Composite events were constructed by selecting events if the EEOF amplitude time series exceeded 1 standard deviation [N = 43 (49) for winter (summer)]. The resulting composites have dimensions lag (-5 to +5 pentads), latitude and longitude. In the plots above, only 4 panels of the boreal winter composite are shown, each separated by 2.5 pentads (i.e. 12.5 days). Plots on the left (right) show composite rainfall and 850 hPa wind vectors for boreal winter (summer). Only values that exceed the 90% confidence limit are shown.

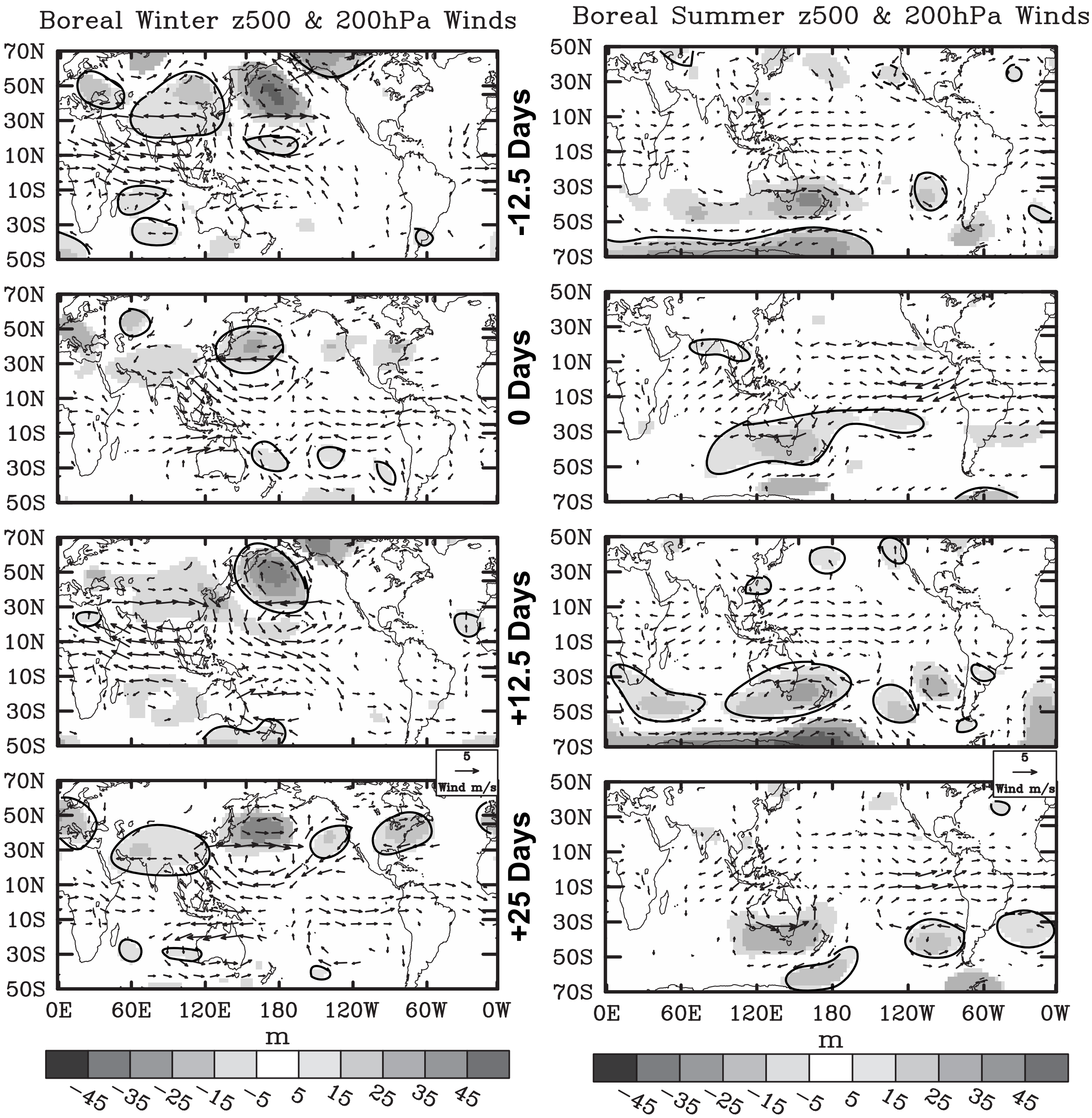

Figure 2. Same as above except for 500 hPa geopotential heights and 200 hPa wind. In this case, encircled shading denotes positive anomalies.

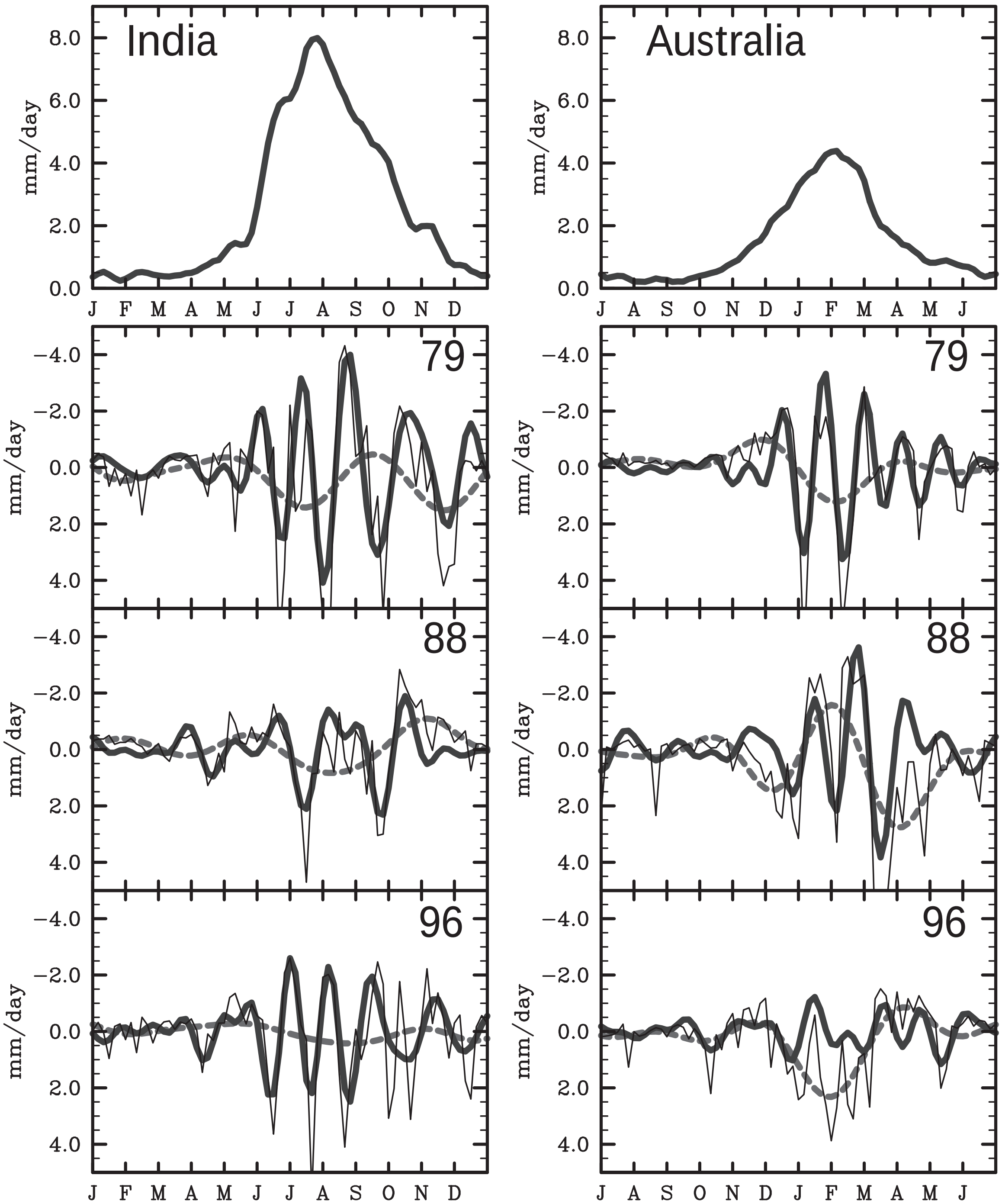

Figure 3. Time series of rainfall over India (left) and Australia (right). Rainfall data is based on pentad values of the satellite and in-situ merged CMAP product of Xie and Arkin (1997) from 1979 to 1999. The data plotted for India (Australia) are the domain averages of the grid points lying within India (Australia, lying north of 25ºS). (top) Mean 73-pentad annual cycle. (lower three panels) The thin black lines are pentad anomaly values, the thick black lines are 30-90 day band-passed values, and the thick dashed lines are 90 day low-pass values for the years 1979, 1988 and 1996.

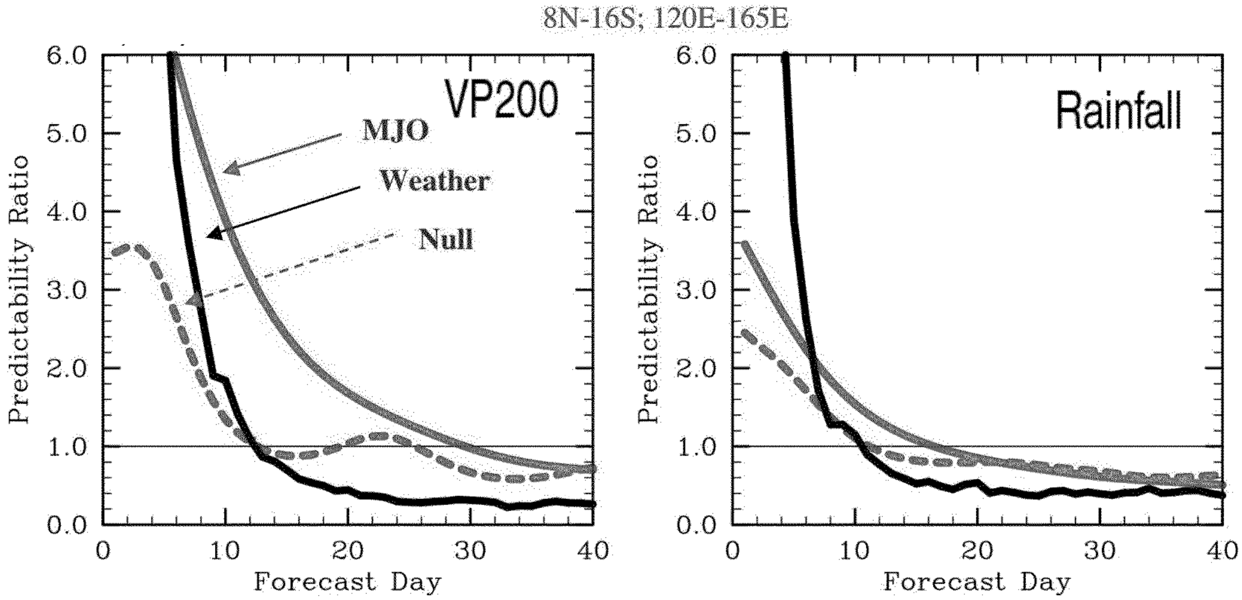

Figure 4. Predictability measure, defined as the ratio of the MJO signal and the MJO forecast error (see Waliser et al., 2003b), versus lead time based on 120 northern hemisphere winter MJO twin-predictability forecast cases for VP200 (left) and rainfall (right) from the NASA/GLA model for 120 active/strong boreal winter MJO cases (solid black), 30 weak/null boreal winter MJO cases (dashed gray) and for unfiltered "weather" variations (using the 120 active MJO cases; solid gray) for the region 8°N-16°S and 120-165°E.

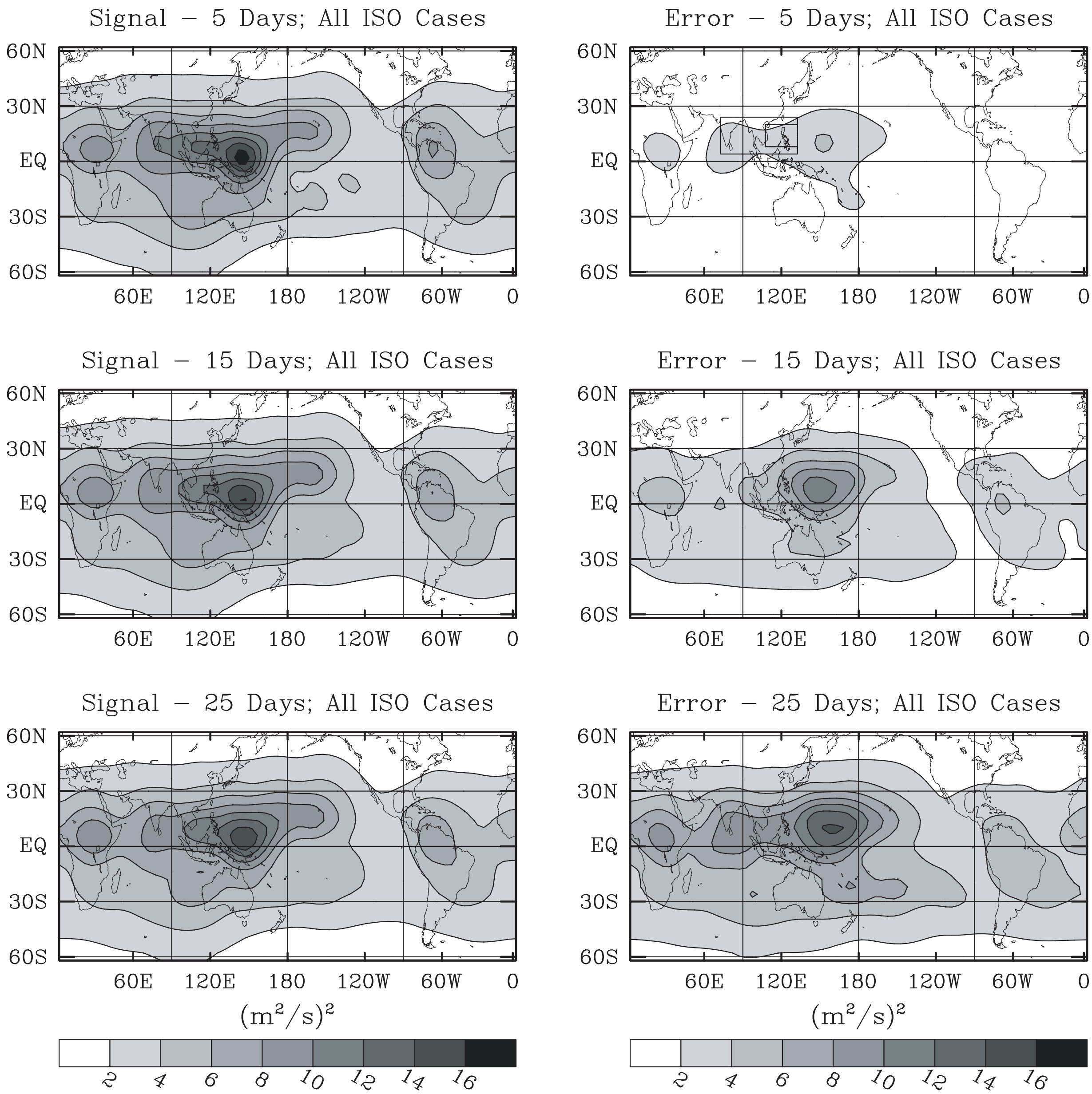

Figure 5. The MJO mean signal (left) and mean forecast error (right) for all the boreal summer MJO cases (N=168) at lead times of 5 (top), 15 (middle), and 25 (bottom) days for filtered (30-90 days) 200 hPa velocity potential (VP200). VP200 values have been scaled by 10^{-12}. From Waliser et al. (2003c).

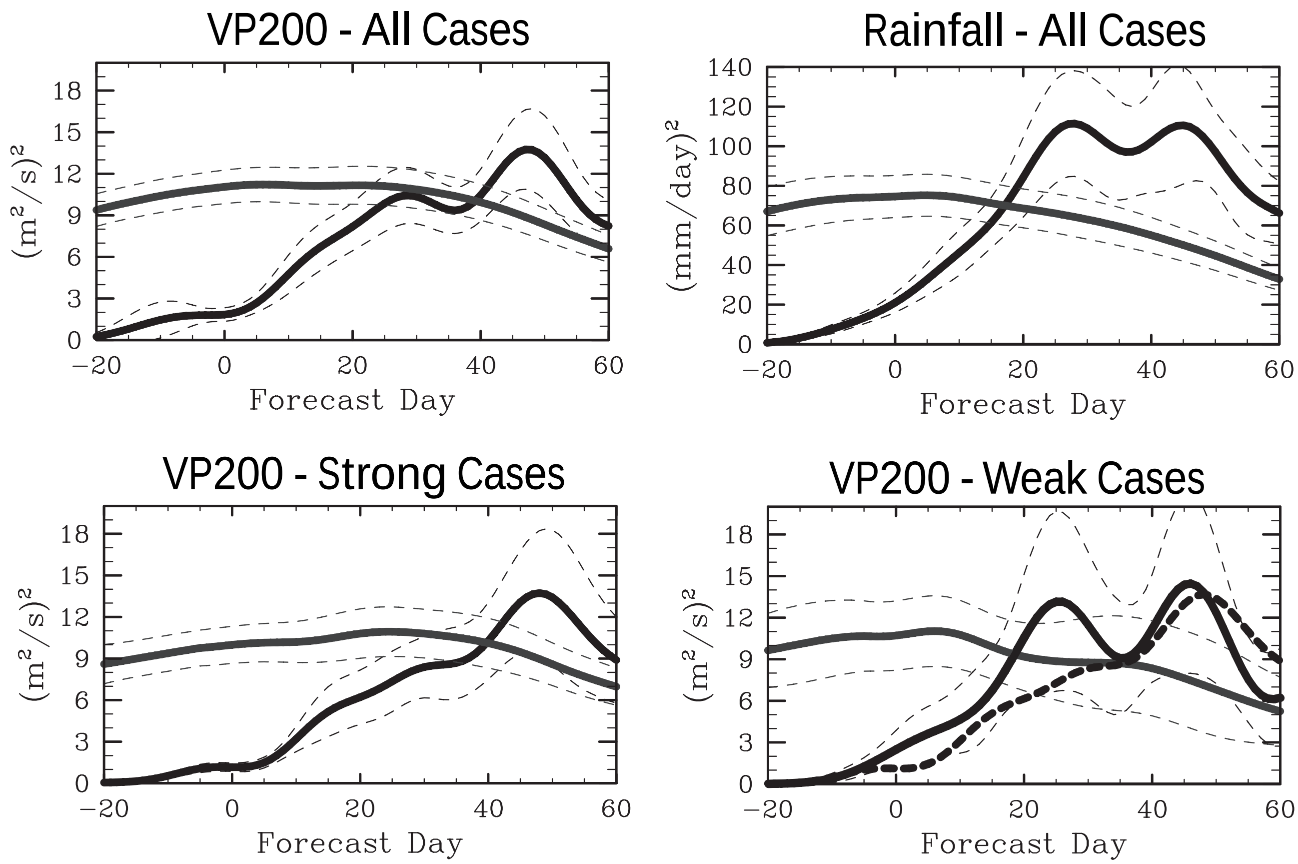

Figure 6. (upper) The thick solid black lines, that increase with forecast time, are the mean squared forecast error for the (30-90 day) filtered (left) 200 hPa velocity potential (VP200) and (right) rainfall, over the region 12^{o}N-16^{o}N and 117.5^{o}E-122.5^{o}E (model grid point at center of smaller black box in Figure 5) for all the boreal summer MJO cases (N=168). The thick solid black lines, that roughly constant with forecast time, are the mean MJO signal for the same quantities, and over the same region and cases. The thin dotted lines depict the 95% confidence limits for the above quantities using a student t-test. VP200 values have been scaled by 10^{-12}. (lower) Same as upper left panel, except that the left (right) panel is based on forecasts using the strongest (weakest) MJO cases (N=80 in each case). The thick dashed line in the lower right panel is a re-plotting of the mean-squared error from the lower left panel to allow for easier comparison between the strong and weak MJO cases. VP200 values have been scaled by 10^{-12}. Adapted from Waliser et al. (2003c).

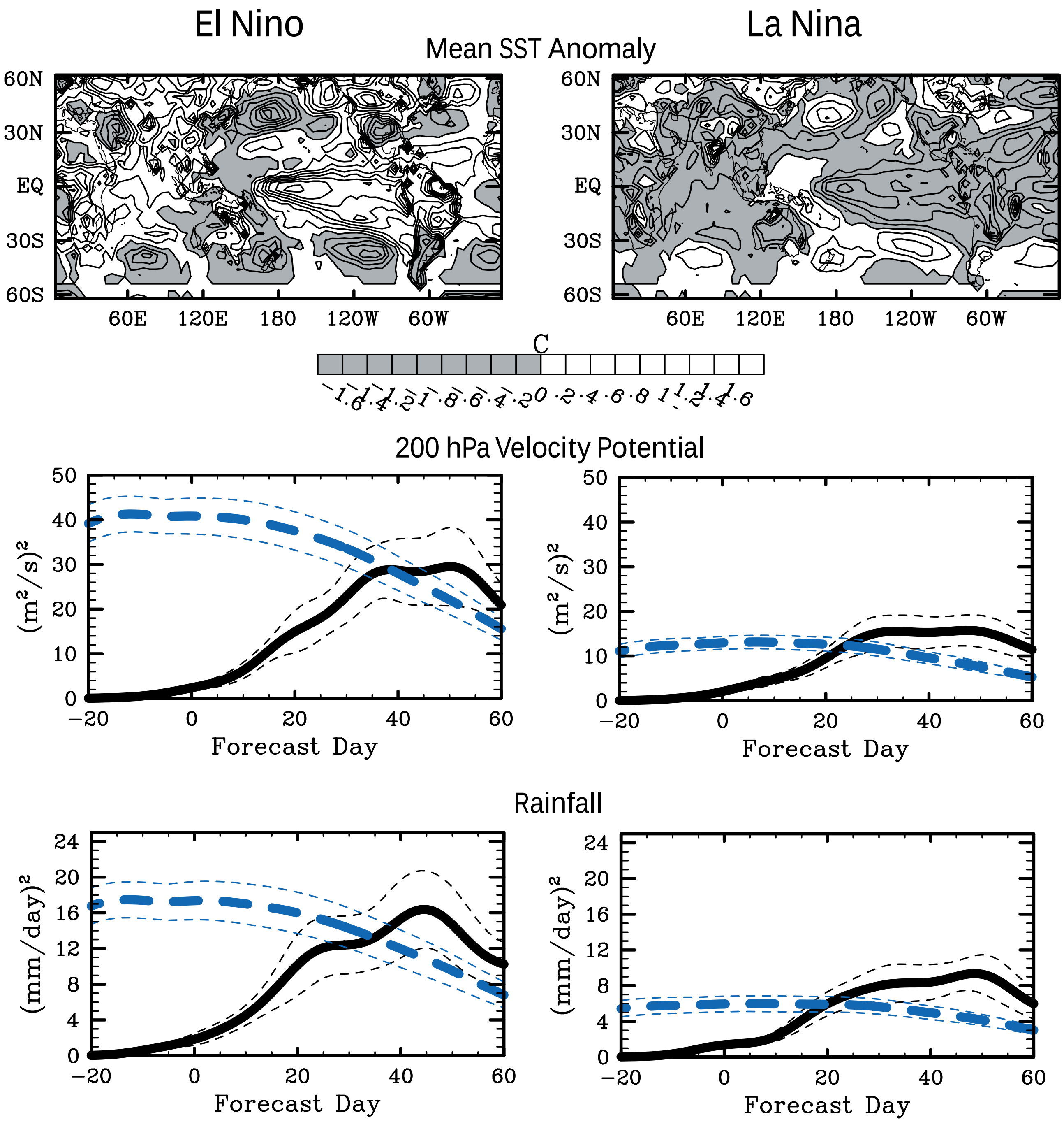

Figure 7. (upper) Annual mean of 12-month evolving perpetual sea surface temperature (SST) anomaly applied to the set of predictability experiments associated with El Nino (left) and La Nina (right) conditions. (middle) The thick solid black lines are the mean squared forecast error for the (30-90 day) filtered 200 hPa velocity potential (VP200) over the western Pacific Ocean (4^{o}N-12^{o}S; 147.5^{o}E-162.5^{o}E) for all the boreal winter El Nino (left) and La Nina (right) MJO cases (each have N=120). The thick dashed gray lines are the mean MJO signal for the same quantities, and over the same region and cases. The thin dotted lines depict the 95% confidence limits for the above quantities using a student t-test. VP200 values have been scaled by 10^{-12}. (lower) Same as middle, except for rainfall.

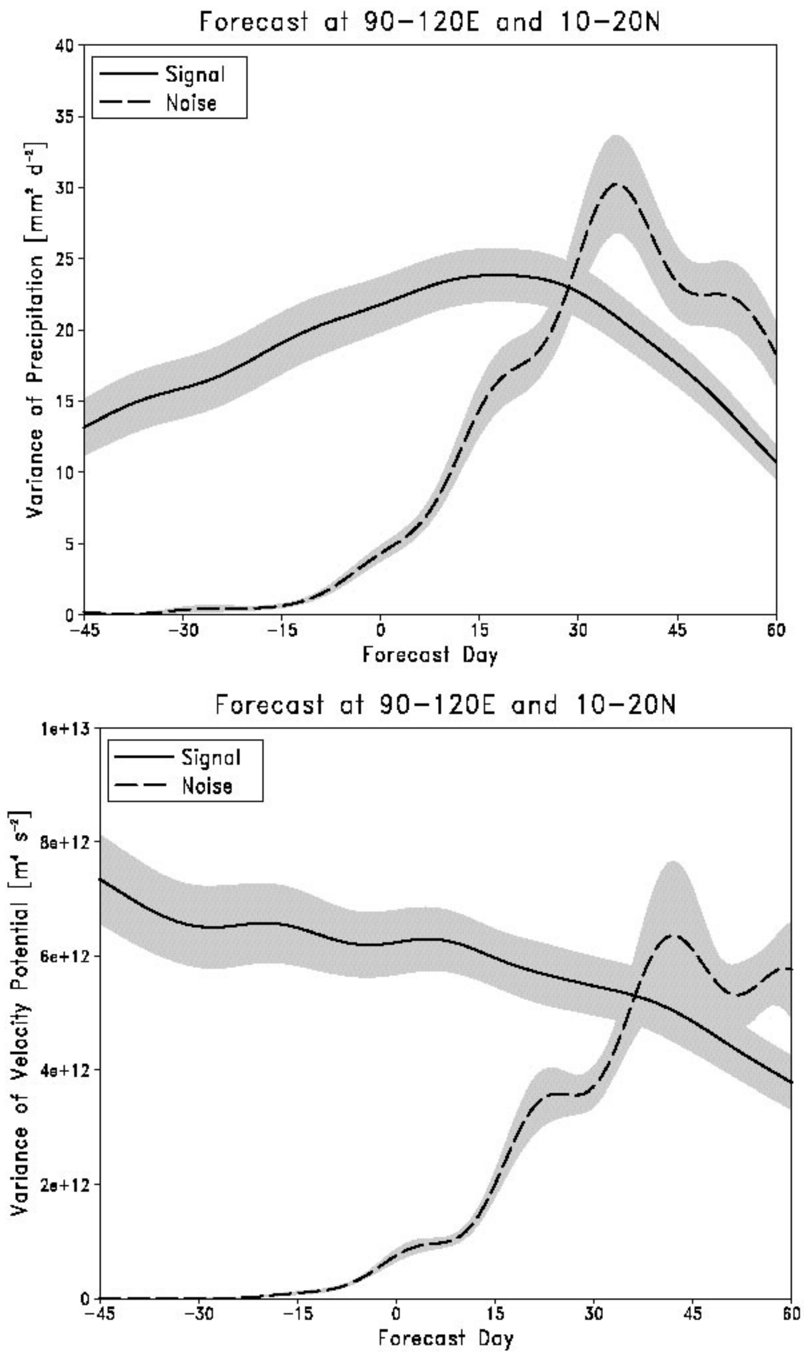

Figure 8. Signal-to-noise ratio of 30-90 day filtered precipitation (top) and 200 hPa velocity potential (bottom) predictions averaged over all four phases of three MJO events. Shadings represent the significance at the 95% interval based on all twelve 15-member ensemble forecasts. All values are averaged over the region 90 to 120 ºE and 10 to 20ºN. Adapted from study by Liess et al. (2004).

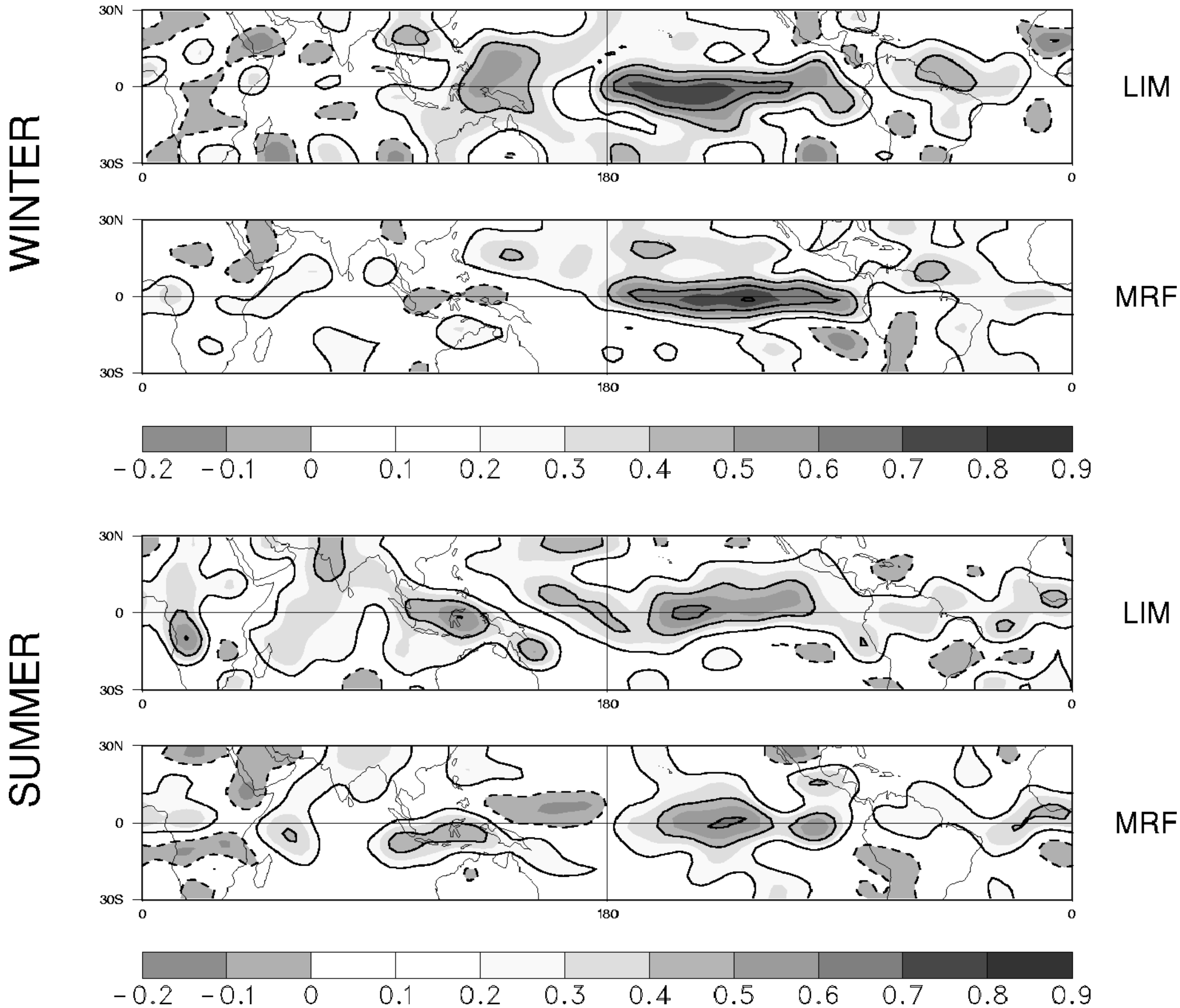

Figure 9. Anomaly correlations between forecast and verification column-integrated diabatic heating using the LIM forecast model (Winkler et al., 2001; Newman et al., 2003) and a research version of the NCEP MRF model (i.e. MRF98) for both the northern hemisphere winter (top) and summer (bottom). Forecasts were made for June-August periods for the years 1979-2000. Solid (dashed) contours indicate positive (negative) values.

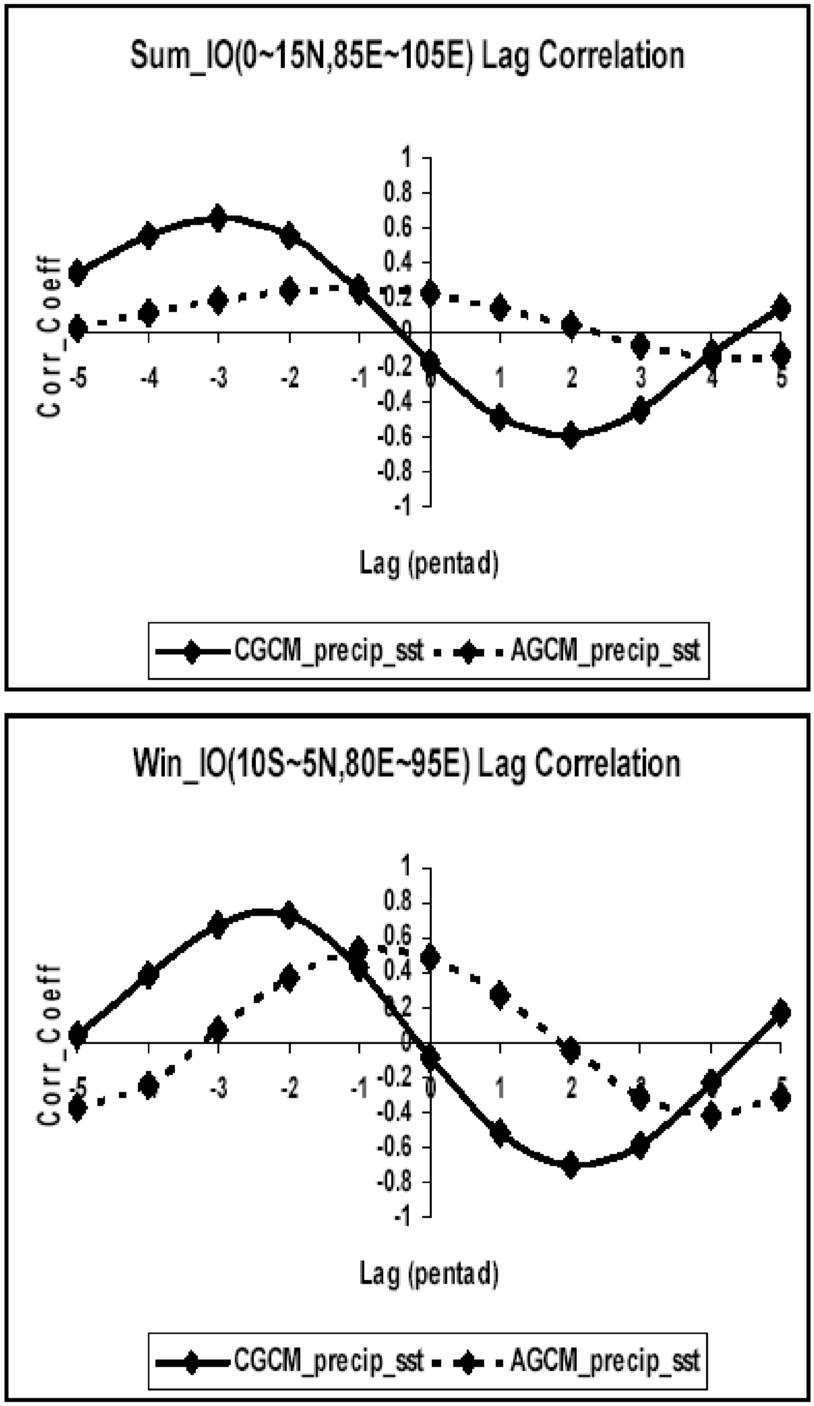

Figure 10. Lagged-correlation values between SST and rainfall anomalies from the NOAA Geophysical Fluid Dynamics Laboratory (GFDL) ocean-atmosphere coupled GCM (CGCM; solid) and the corresponding atmosphere-only GCM using SSTs specified from the CGCM simulation (dotted). The top plot is for the boreal summer period and is averaged over 85-105°E, 0-15°N while the bottom plot is for the boreal winter period and is averaged over 80-95°E, 10 °S-5°N. From Zheng et al. (2004).

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